# striolae

*LARS STENBERG*

## FULL SCALE FROST HEAVE TESTS

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Uppsala 1979

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# FULL SCALE FROST HEAVE TESTS

By

Lars Stenberg
fil. kand., Stockh.

Doctoral Dissertation
to be Publicly Examined in the Lecture Hall of the Institutes of Geography and Geology on January 18, at 10 a.m. for the Degree of Doctor of Philosophy (according to the Royal Proclamation No. 327, 1969)

SOCIETAS UPSALIENSIS PRO GEOLOGIA QUATERNARIA

UPPSALA 1979

ISBN 91-7388-009-4
ISSN 0348-4386

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Printed in Sweden 1979
Societas Upsaliensis Pro Geologia Quaternaria

# FULL SCALE FROST HEAVE TESTS

LARS STENBERG

Stenberg, L., 1979 01 05:Full scale frost heave tests. *striolae*, 1979: 2, 36 pp. ISBN 91-7388-009-4, ISSN 0348-4386.

The frost susceptibility of soils is usually determined after laboratory freezing tests. The results are to a great extent dependent on the design of these tests. One major drawback of this form of tests consists in the difficulty of interpreting the results in terms of field behaviour.

In order to discover the frost behaviour of soils in the field, a full scale test was initiated by the National Road administration *(VV)*. Its purpose was to develop a method whereby most of the known frost heave parameters could be controlled, and to evaluate the relevance of the method chosen to the classification of the frost susceptibility of soils.

The test was performed as a laboratory freezing experiment. Four cylinders were constructed of concrete rings. The cylinders were filled with layers of soils with different susceptibility to frost. The water level was kept constant. The test continued through four winters, during which soil temperature, frost depth, frost heave, frost index, and accumulated water were recorded.

The results showed that the method chosen can be used for classification of frost susceptibility. Difficulties arose, however, in the interpretation of the results, mainly because of the layering of different soils. Future tests should be carried out with one soil in each cylinder. It was not possible to determine the influence of permeability on frost heave. The decline of the thermal gradient seems to be more important for frost heave rate than the increase in lead pressure, although the load pressure affects the amount of heave, which is relevant to the frost heave on roads.

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## Introduction

The National Swedish Road and Traffic Research Institute (VTI) operates a continuous research program on the possibilities of establishing a classification system of soils, with regard to their behaviour in the winter and especially their susceptibility to frost. The present system is based on both capillarity tests and the particle size distribution curve, i. e. particle size fractions in percent by weight.

In simple terms we may say that the soil is divided into the frost susceptibility groups (according to the percentage of the fine-grained material).

I »not susceptible»

II »somewhat susceptible»

III »highly susceptible»

This rather crude classification has proved unreliable. It is now generally held that the most reliable method of classification is to apply a standard freezing test to the soil in the laboratory.

At the request of the National Road Administration (VV) VTI has developed a flexible and easily transportable apparatus for direct freezing of soil samples. However, these tests only give a relative idea of the frost heaving capacity of a soil. The method of performing these tests is also of great importance. In the laboratory it is possible to provoke frost-heaving in a soil sample (e. g. sand) not normally susceptible and vice versa: the heaving potential in a highly frost-heaving soil can be reduced to vanishing point.

In order to obtain a correct interpretation of the results from a laboratory test it is necessary to compare the results with the field behaviour of the same soils.

The Road Administration was interested in a study of the critical frost-heaving parameters in the field. At its request a full-scale frost-heaving project was started at Sälen in 1972. The object was to obtain information on the behaviour of soils under controlled conditions, and on the reliability of the testing method. The construction of the research station is described in VTI internal reports. This project was named »Sälen».

The following discussion is a summary of the following reports.

1. Projekt Sälen. Tjällyftningsförsök i fält. Del I. Fältiakttagelser. *VTI meddelande 41.* 1977.

2. Projekt Sälen. Tjällyftningsförsök i fält. Del II. Temperaturförhållanden och energibetraktelser. *VTI meddelande 101.* 1978.

3. Project Sälen. Full-scale frost heave test. Part III. Thermal conditions. Basics of thermal calculations. *VTI meddelande 106.* 1978.

## Frost action

### *Frost action on roads*

Frost heave is mainly an effect of accumulation of water in the frozen layers of the soil, provided the soil is frost susceptible. Sand and gravel are examples materials not susceptible to frost. Increasing the content of fine grains in the soil will exaggerate the frost susceptibility. When the proportion of fine-grained material is very high, as in clay, the rate of frost

heave will decrease according to the decline in permeability.

Thus for frost heaving to occur the following conditions must be realized:

1) $0^{o}$C-isotherm must penetrate the soil.

2) The soil must be susceptible to frost.

3) Water must be available to the soil.

The frost heave can be either uniform or differential. The uniform frost heave will appear where the soil conditions and the humidity are uniform along and across the road. This should support a uniform frost penetration of the road, provided the water sources are uniformly distributed. The frost heave generated will not then be noticed by the road users.

*Damage to Roads by Frost Heave.* – The negative effects of frost heave on roads relate to serviceability and travel comfort. This will be illustrated by a few examples.

To the road user the most obvious results of frost action are the cracks in the paving. The cracks are either transversal or longitudinal. Low temperatures give rise to contraction forces in the paving, usually resulting in transversal cracking. The differential frost heave causes the longitudinal cracks. According to Gandahl (Gandahl, 1974), the cracks appear at the verges of broad and narrow roads, and in the middle of intermediate roads.

Another type of frost heave action consists in the bulges, which give rise to pot holes in the paving. The pot holes appear at the spring thaw, when the sodden base layer loses its bearing capacity and the pavement collapses under the pressure of the traffic. One common result of decreased bearing capacity are the tracks in the road. The main cause is insufficient draining of excess water. On gravel roads the loss of bearing capacity during the spring thaw is the most serious problem.

Variations in composition of the subgrade soils, as well as in ground water level in the longitudinal sections of the road will give rise to differential frost heave. This affects the comfort of the traveller.

Differential frost heave will also appear when there are abrupt changes in the subgrade composition, e. g. rock crossings, underlying culverts, transitions to bridges and viaducts, when the soils are frost susceptible, close to ground water level or water-bearing strata. Two conventional ways of achieving continuous transition are:

1) Mass shifting and refilling with soils not susceptible to frost.

2) Insulation.

In both cases the masses should be wedged with the point directed away from the rigid or non-frost heaving section, in order to create a continuous transition between different kinds of underlying strata.

Frost heave can also be partly impeded by moisture barriers, such as a sandy layer (capillary cut-off) or encapsulation in plastic film, asphalt or other dense materials which prevent the flux of moisture and the resulting water accumulation, partly by blocking the penetration of the $0^{o}$C-isotherm into the lower strata by means of insulation or frost accumulating layers such as bark or peat. The frost accumulating effect emanates from the high water content. There are many other methods, such as reduction of permeability by addition of stabilizers, e. g. Portland cement, lime and bitumen (Johnson *et al 1975).*

*Positive Effects of Frost Action.* – The frozen water in the road material has a strongly stabilizing effect. This allows for a higher axle load, which increases the transport capacity.

*Freezing without Frost Heave.* – The higher the load pressure the lesser the frost heave. In physical terms the load pressure counteracts the frost heaving pressure, and consequently the direction of frost heave. The ability of soils to develop frost heaving pressures is of importance for designing rigid constructions such as retaining walls, house and bridge foundations etc. Determinations of the frost heaving pressures of soils have also been the subject of frost susceptibility classification systems.

## Classification of the frost susceptibility of soils

The main part of the classification of the frost susceptibility of soils (frost heave capacity) from direct freezing in the laboratory was done by G. Beskow, being presented in his comprehensive work »*Tjälbildningen och tjällyftningen med särskild hänsyn till vägar och järnvägar*» (Beskow 1935). In this work he shows how the primary and determining frost heave parameters, e. g. thermal conditions, load and distance to ground water level, affect the development of the frost-heave process. He also discusses the influence of the properties of the soil, such as mechanical and mineralogical composition, specific area, pore structure, water content etc. As the mechanical composition of the soil to a large extent determines its physical properties, all but a few classification methods are based on »the particle size distribution curve» (Stenberg 1971, Alfheim 1972). The capillarity test is one of the exceptions. In Sweden we have adopted Beskow' s method, but Williams also developed a method for capillarity determination (Williams 1967, Brox & Saetersdal 1968).

A combination of the above methods (the particle size distribution curve and the capillarity test) would improve the reliability of the classification. However, the capillarity test might produce divergent results, in comparison with freezing tests. Observed frost heave, i.e. accumulation of water as ice, is a result of the suction of water from the ground water level to the freezing front. The capillarity test is based on the assumption that the capillarity is directly related to the frost heaving capacity of the soil, i.e. the suction developed at the freezing front is proportional to the capillarity.

It has been shown that the suction developed also depends on the rate of frost penetration (Saetersdal 1972).

Very comprehensive tests have been performed by Kaplar with a view to finding one or more specific soil properties or parameters based on the particle size distribution ( e.g. $d_{10}$, $d_{60}/d_{10}$, $d_{30}/d_{10}$, void ratio etc) for the classification of soils according to frost susceptibility (Kaplar 1965, and 1967).

Kittridge and Zoller carried out regression analyses on soil parameters based on particle size distribution (Kittridge and Zoller 1969). The results did not show any easily definable relationship to frost heave. Serious problems still beset the creation of reliable classification systems. It is generally believed that the most reliable method for determining the frost susceptibility could consist in standardised freezing tests in the laboratory (Stenberg 1971).

## Laboratory freezing tests

As early as 1914 Simon Johansson demonstrated that frost heave is caused by the accumulation of water at the frost front, which results in a higher water content in the frozen layer of the soil (Beskow 1935). If the heaving is to be studied the soil sample must have free access to a so-called open system. The soil is frozen in insulated cylinders which can resist the pressure of expansion directed towards the cylinder walls. The water supply is usually located at the bottom of the sample, and the freezing maintained by blowing cold air at the top. The soil is free to expand upwards. When the soil freezes it also adfreezes to the cylinder walls. This gives rise to a force, the adfreezing force, which, considered as a friction force directed against the direction of expansion, constitutes a restraint on heaving. Beskow solved this problem by dividing the cylinder into separate rings which adfreeze to the frozen heaving layer of the soil sample. This reduces »frozen friction» to friction between the unfrozen soil and the cylinder wall of the ring, »unfrozen friction».

In addition to »ring tests», Kaplar, among others, has carried out experiments with tapered cylinders. The tapered design reduces the adfreezing force as the force component in the direction of heave is reduced. A comparison of »Multi-ring» and tapered cylinder tests is shown in fig.1. The adfreezing force can be reduced by covering the inside cylinder walls with grease.

The apparatus developed at the National Swedish Road and Traffic Institute (VTI) uses freezing from below, which obviates the adfreezing forces and reduces the friction to »underfrozen» friction The prototype was designed by Dr Sven Freden (VTI) and tested in frost heave trials on different minerals (Stenberg & Kiiver 1971).

The present cylinder is much larger, Ø 110 mm by 150–200 mm high. The classification is based on the heaving rate observed at at constant heat flow (Kittridge & Zoller 1969, Stenberg 1971). Freezing is produced by Peltier elements and load pressure exerted by different weights on the top of the sample. The freezing is governed by an electronic device developed at VTI.

In terms of the physics of soil freezing, I find it more correct to refer frost heave to heat flow than to e.g. a constant or continuously lowered surface freezing temperature. This point has also been made in *VTI Internal Report No 46.*

The apparatus developed permits fairly fast freezing. The present tests are performed in 12 hours but this period can be reduced. These tests give only relative classifications.

In order to improve the accuracy of classification by laboratory freezing, the test results must be related to field conditions. Knowledge of the behaviour of identical soils during the winter, i.e. under natural freezing conditions, is necessary. The first step in this direction was taken during the operation of the »Sälen»-project. The object was to study the frost heaving behaviour of frost susceptible soils under controlled conditions, i.e. as close to laboratory test conditions as possible, and to evaluate a technique for this type of full-scale freezing tests.

## Project Sälen

At the request of the National Road Administration full-scale frost heaving

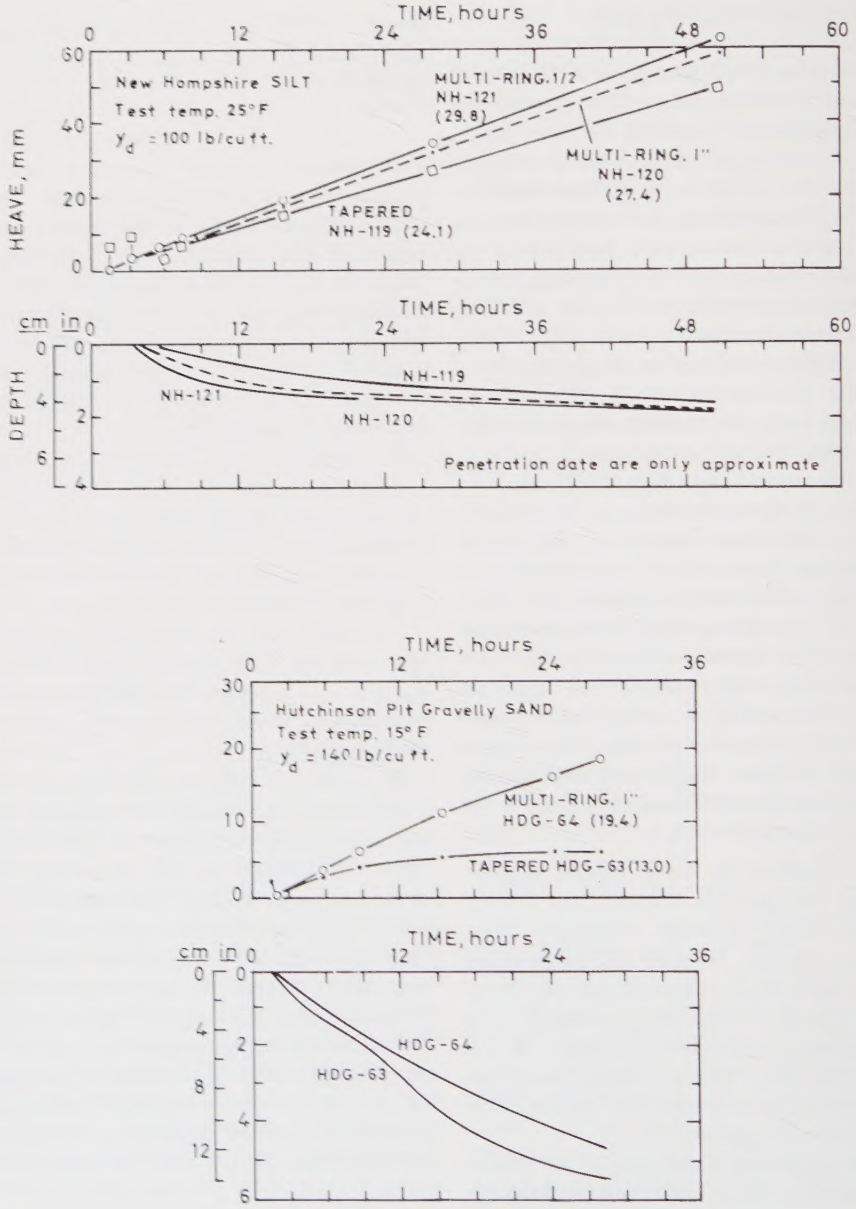
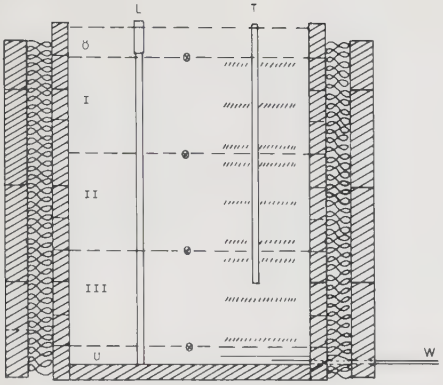



Fig. 1. Comparison of test results between »multi-rings« and tapered cylinders (from Kaplar 1971). The reduced frostheave in the tapered cylinders is considered depending on the adfreezing forces.




Construction and instrumentation of the Freezing Cylinders.

| | |
|---|---|
| ÖU | Base course material (sandy gravel) VTI 90102 |
| I-III | Three layers of test material |
| | Insulation (Rock wool) |
| | Concrete rings |
| L | Vertical movements meter |
| T | Frozen earth indicator |
| | Resistant thermometers |
| W | Water pipe |
| | Metallic net |

Fig. 2.

studies on frost susceptible soils under controlled conditions were initiated. The purpose was to examine the possibilities of the method *per se*.

The experiment was designed and carried out as a laboratory test. Consequently, the same frost heaving parameters had to be controlled as in a laboratory test. To meet this condition, the freezing cylinders had to be as fully instrumented as possible.

The report and discussion of the test results was devided into two sections. The general section is presented in *VTI Meddelande No 41* and the thermal observations are treated in *VTI Meddelande No 101*.

### *Locality*

The first step was to find a locality with a high frost index not too far from Stockholm, and where it was possible to have people available for the operation of the test. The Sälen area in north-western Dalarna was found to meet these conditions, and the local road administration kindly put people at our disposal for the construction and future maintenance of the test station, and for the regular readings of data.

### *Description*

The field trial was carried out as a full-scale laboratory test. The freezing cylinders were built up with concrete rings. The outer cylinder carried the surrounding soil pressure, and the inner cylinder contained the soils to be tested. The space in between was packed with mineral wool (Fig. 2). The cylinders were filled with three different soils in separate layers (Fig. 3). As the tests were primarily intended to provide general information on field performance, the number of cylinders was limited to 4, designated FC FC 1—FC 4. The reference soil chosen was a fine-grained silt, highly susceptible to frost, an ice-lake sediment from Lake Siljan. The other two test soils were a somewhat less susceptible coarse grained silt, a wave washed beach sediment, and a till. Particle size distribution curves of the soils are presented in Fig. 4.

### *Instrumentation*

It was stipulated in the the test that the control of the vertical soil movements as far as possible should be of the same qualitative precision as in a laboratory test.

| Layer thickness | Cylinder 1 | Cylinder 2 | Cylinder 3 | Cylinder 4 |
|---|---|---|---|---|
| 15 cm | Sandy gravel | Sandy gravel | Sandy gravel | Sandy gravel |
| 60 cm I | Till | Fine silt | Fine silt | Coarse silt |
| 60 cm II | Fine silt | Till | Till | Fine silt |
| 60 cm III | Fine silt | Fine silt | Coarse silt | Till |
| 15 cm | Sandy gravel | Sandy gravel | Sandy gravel | Sandy gravel |

Fig. 3. Layering of test material in freezing cylinders FC 1–FC 4.

The amount of frost heave and settlement was measured for every separate soil. Air temperature was continuously recorded on a termograph and the soil temperature was measured each week at the soil interfaces. The water supply came from separate water containers stored in temperate surroundings. The water level was kept relatively constant in the containers, and this simulated ground water level may be presumed to have remained constant. The frost depth, defined by the frozen zone of the frost depth indicator, was read by observation. The instrumentation is shown in Fig. 2. The details of research station and equipment were published in *VTI Internal Report No 102* (Stenberg 1973).

### *Measurements and principles for evaluation of results*

The instrumentation allowed the reading of both the gross heaving of each soil and the net heaving, i.e. heaving observed at the ground surface.

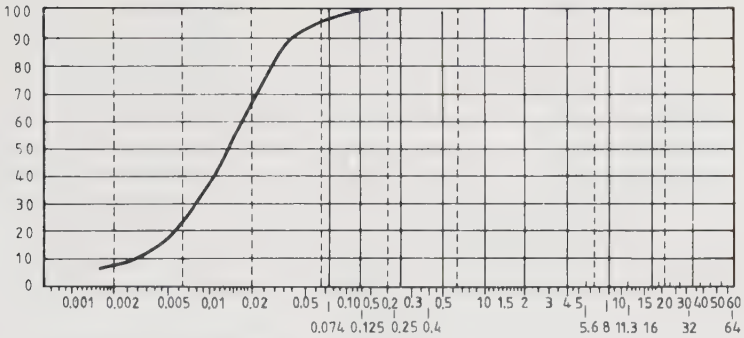
The recorded frost index was related to gross frost heave and frost penetration in order to examine the general connection between these parameters.

The load pressure was established by the overlying soils and adfrozen rings. The observed soil temperatures were used for calculating the termal gradients, which were assumed to be linear within each interval. This simplification was considered permissible, as the test was intended to provide general information on thermal conditions and heat exchange. The amount of heat flow is of interest in the search for a factor which could be used in calculations for transferring laboratory frost heave data to frost-heaving behaviour in the field.

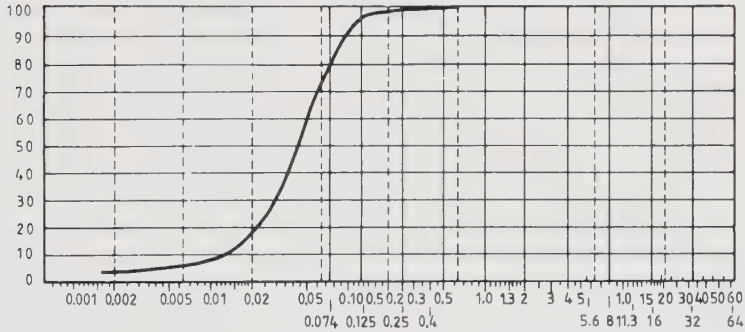
During the frost-heaving period the accumulated water was measured. At frost heave maximum the frozen soil core samples were obtained with the help of technique to obtain the water content of the frozen soil.

At the end of the test program, when the freezing cylinders were dismantled, there were indications that the concrete rings had adfrozen hard to the soil and followed the frost heave. Controls during the winter also showed that the frost heave close to the cylinder walls had decreased by about 5–7 % of total heave.

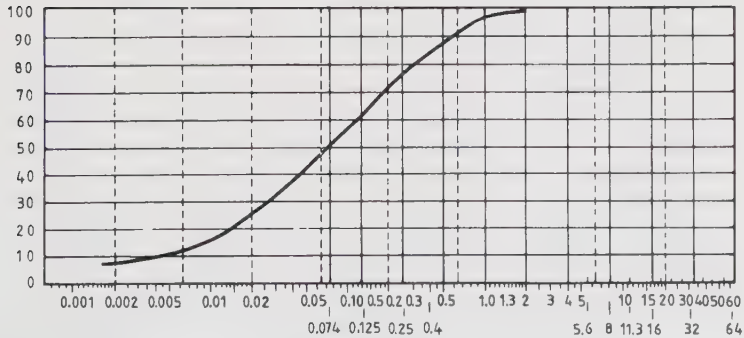
Capillarity and permeability of the soils were determined in the laboratory (Table 1 below).




A. Silt from Vika (Mora)




B. Silt from Ullvi (Leksand)




C. Till from Nordbäck

Fig. 4. Particle size distribution curves of the test material in FC 1—FC 4. All soil samples come from the province of Dalarna.

*Table 1. Capillarity and premeability of the test soil.*

| | *Cap* | *Perm* |
|---|---|---|
| Fine silt | 7,2 m | $2 \times 10^{-8}$ m/s |
| Coarse silt | 6,0 m | $1 \times 10^{-7}$ m/s |
| Till | 5,3 m | $8 \times 10^{-9}$ m/s |

*The permeability determination was performed at:*

| | *Water content* | *Dry density* |
|---|---|---|
| Fine silt | w = 15 % | $\gamma_d$ = 1,64 t/m$^3$ |
| Coarse silt | w = 15,5 % | $\gamma_d$ = 1,65 t/m$^3$ |
| Till | w = 12 % | $\gamma_d$ = 1,79 t/m$^3$ |

## Presentation of test results

The most common, and at the same time the most descriptive, form of reporting field observations is to show frost index, frost heave and frost penetration in the same diagram, sometimes supplemented by soil profile and ground water level. In the presentation of the results from the Sälen-tests a water content profile has been added to the diagram, showing the water content of the samples received from the drill-hole, Fig. 5. The drilling was executed approximately at frost heave maximum. The ground water level, considered constant, is situated in the interface between the lower base course material and the test soil 1,8 –2,0 m below surface. The accumulated water volume is graphically shown as a function of time in diagrams (Fig. 6). The temperatures at the dividing lines between two soils are also shown in diagrams as a function of time (Fig. 7). The reported measurements cover the period 1973–1977.

The complete report on the measurements 1973–1976 is presented in *VTI Meddelande No 41.* Soil temperature data 1973–1977 and frost data 1976–1977 are illustratedin *VTI Meddelande No 101.* A more detailed description of the basic principles, on which the termal calculations were based, is given in *VTI Meddelande No 106.*

*Study of the observation results*

The study sought to anwer such questions as

1 a. Is there an definable relation between frost heave and frost index?

1 b. If so, can it be used in predictions of the severety of frost heave?

2 a. Is there a straightforward correlation between frost heave and frost penetration?

2 b. Are they perceptibly correlated with the frost index?

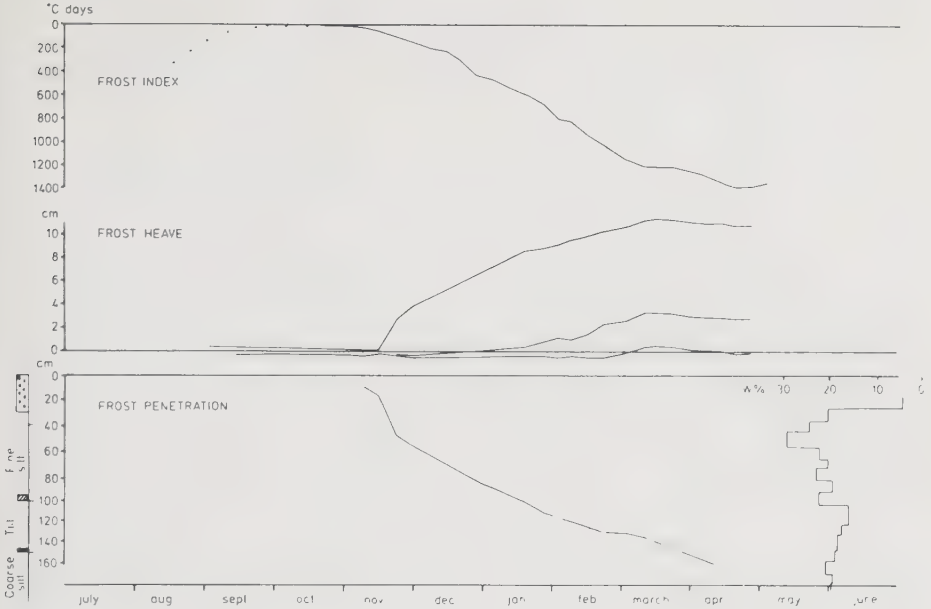
3 a. Can frost index be converted into terms of energy exchange during the freezing process ?

3 b. If so, can it be used according to 1b?

4. Is it possible to use the energy exchange in translations of laboratory test data to field behaviour data?

Fig. 5. FC 3 1976–1977. Frost index, frost heave, frost penetration,water content at frost heave maximum and soil profile have been drawn into the diagram. A= Total (net) frost heave. B= Frost heave in till and coarse silt. C= Frost heave in coarse silt.

Fig. 6. Accumulated volume of water (V) and corresponding frost heave (H) in FC 1–FC 5 during the winter 1976–1977.


°C days
FROST INDEX
cm
FROST HEAVE
cm
FROST PENETRATION
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Till
Coarse Silt
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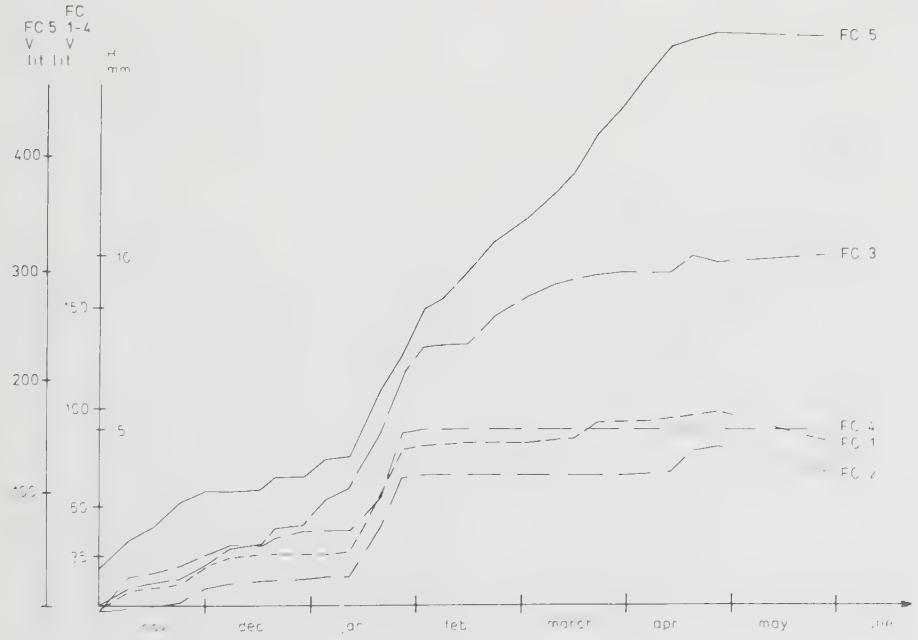
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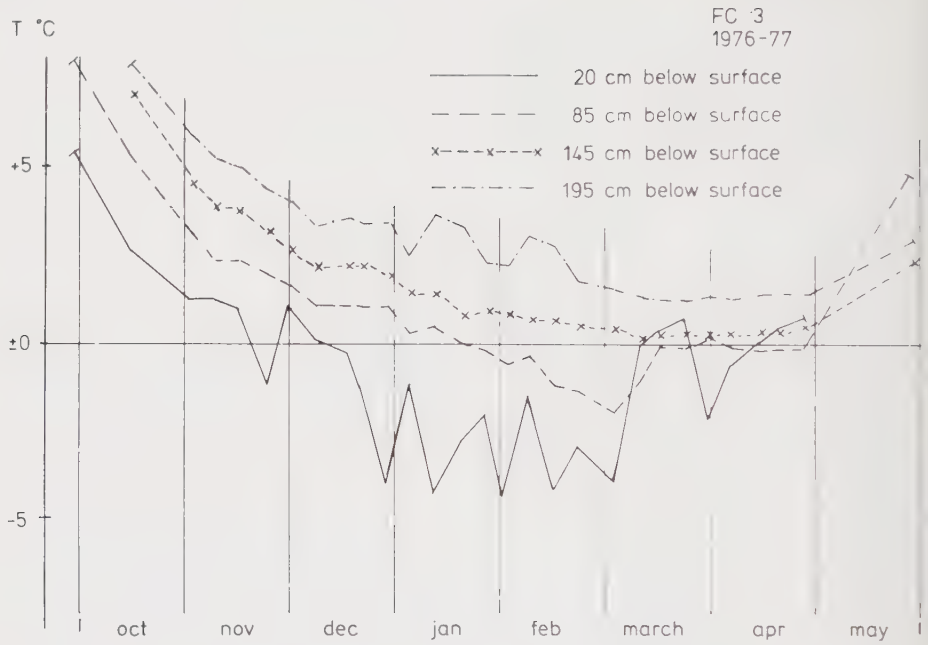


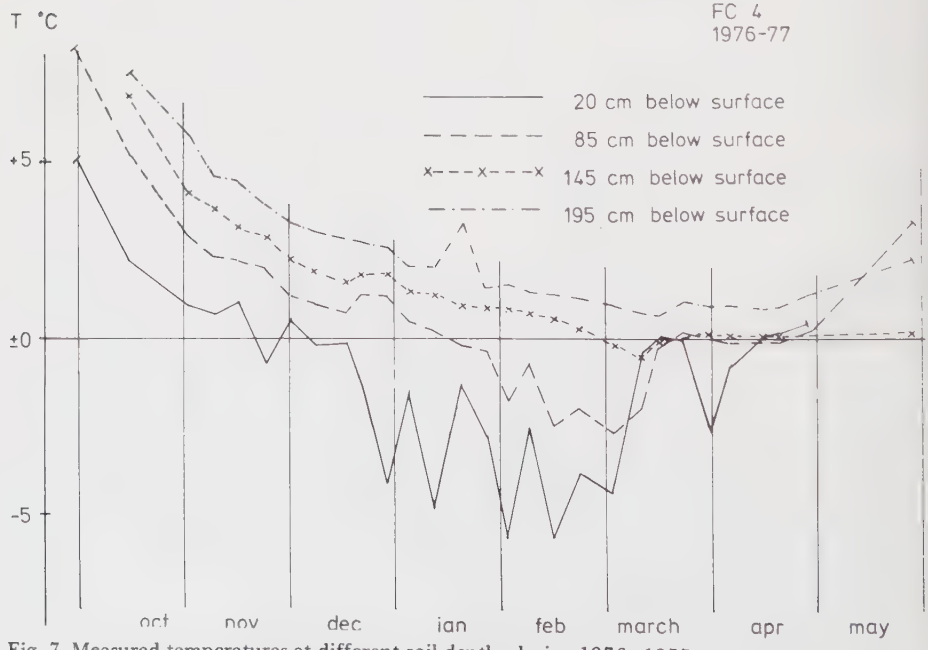


**Fig. 7. Measured temperatures at different soil depths during 1976–1977.**

The received data were processed according to theories based on empirical field and laboratory observations.

### *The relation between frost index, frost heave, and frost penetration*

The main cource of events during the period 1973-1976 is illustrated in diagrams, Fig. 8. The frost heave curves show the net heave of the frozen soil pile. The lower curves show the vertical movements as a sum of the two lower soil layers, S2, and S3.

As frost heave, for natural reasons, is greatest in the top layer S1, the degree of frost heave in this layer grossheave, was plotted against the corresponding frost index in Fig. 9. There is obviously no simple relationship to interpret. Fig. 8 indicates that the inclination of the frost index curve, i.e. the frost intensity during the time intervals which the different soil layers are freezing, varies in different years. In Fig. 10 illustrates frost heave in relation to frost intensity. No direct relationship is apparent, although one can discern a decreasing frost heave with increasing frost intensity, i.e. decreasing average temperature in the time interval.

A summary of the total netheave in 1972—1976 reveals an interesting connection with the frost index, which is shown in Fig. 11. A simple interpretation says that a very small frost index produces frost heave localized to the top layer. At an increasing frost index the frost heave increases to optimum and then decreases. This is undoubtedly correlated with frost intensity. An interesting point is that both Horiguchi (Horiguchi 1975) and Loch & Miller (Loch & Miller 1975) obtained similar and comparable curves in laboratory tests. Horiguchi plotted frost heave against heat flow, while Loch & Miller plotted frost heaving pressure against the termal gradients, which are proportional to heat flow.

The frost index was originally used in calculations of frost depth. Comprehensive data on this subject are found in *Frost i jord, No 17.*

In a number of diagrams both frost depth and frost heave were plotted against frost indices relating to the different soil layers (Diagrams 24—34, *VTI Meddelande 41*). These implied that frost penetration was very little affected by variations in frost intensity, which supports the use of the frost index in calculations of frost depth. However, the accuracy decreases with an increasing frost depth. The frost heave in S1 shows a somewhat wider dispersion.

In the underlying layer S1 the degree of frost heave is less affected by frost intencity, and a linear relationship to frost index can be observed in FC1 and FCs. In FC3 the slope is also found to be the same in all three winters. The layer S2 also shows signs of a relation between frost heave and frost penetration (This is illustrated by Fig. 13). There is a hint of an increasing frost heave together with decreasing penetration, and conversely, in the curves when plotted against frost index. This indicates that the frost index does not itself determine the amount of frost heave. The relations received indicate that, in considering the frost heaving problem as a process of heat exchange, we must first consider the water content *in situ* of the soil.

This is supported by a Canadian investigation of frost depth at different localities related to frost index (Joynt & Williams 1973). They found that the thermal properties of the soil, as determined by the moisture content, also defined the frost depth.

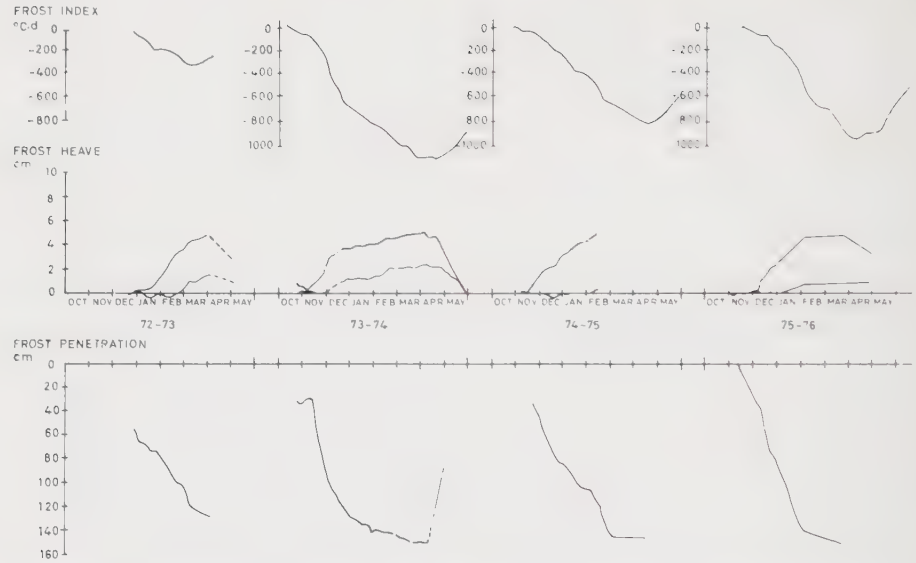


Fig. 8a. FC 1. Frost index, frost heave, and frost penetration during the observation period 1972–1976.

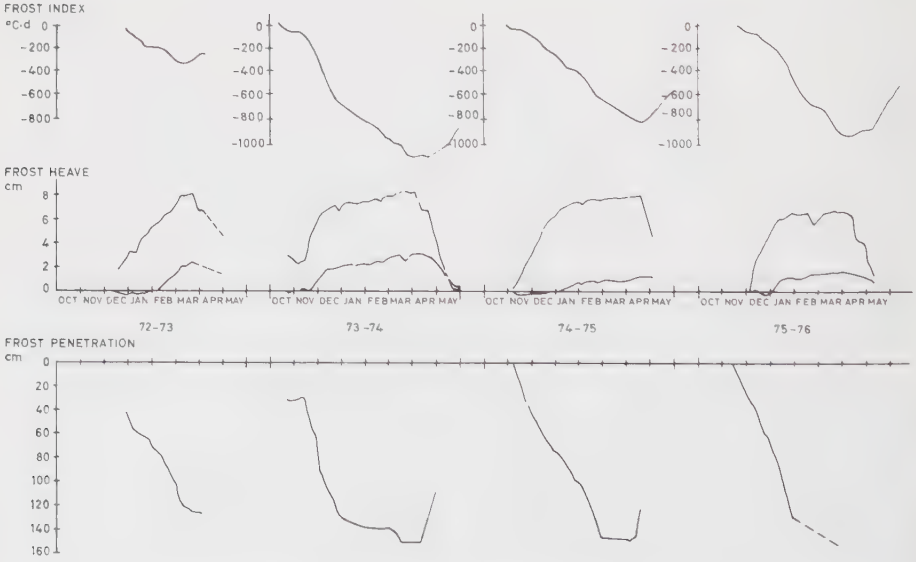


Fig. 8b. FC 2. Frost index, frost heave, and frost penetration during the observation period 1972–1976.

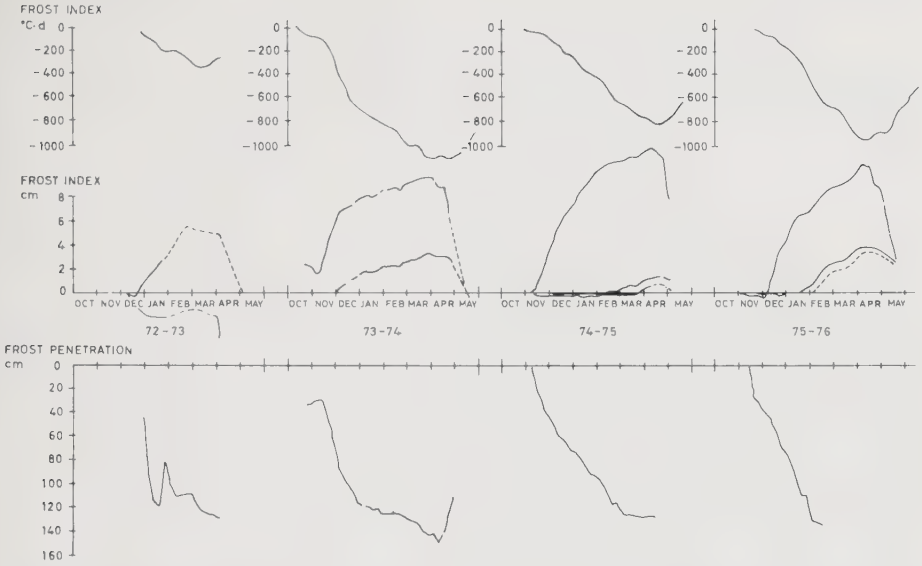


Fig. 8c. FC 3. Frost index, frost heave, and frost penetration during the observation period 1972-1976.

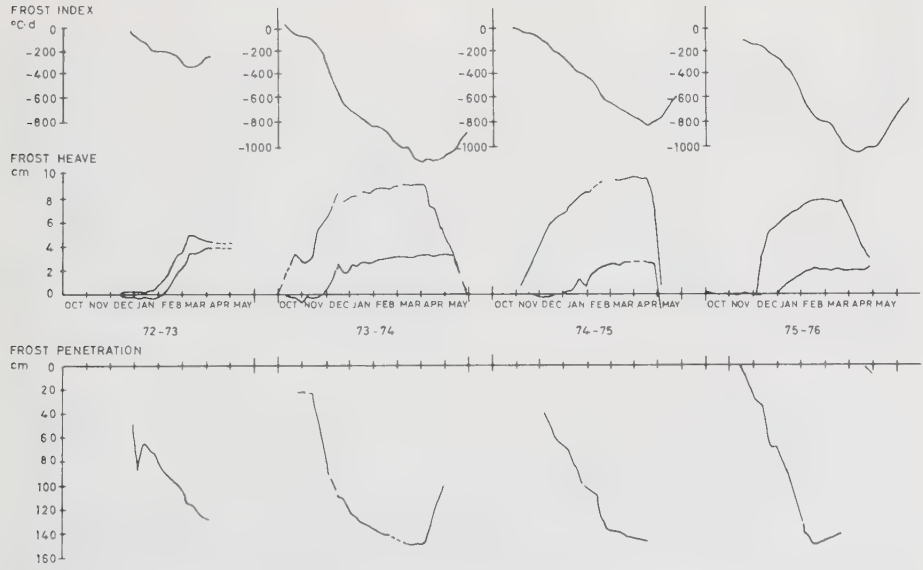


Fig. 8d. FC 4. Frost index, frost heave, and frost penetration during the observation period 1972–1976.

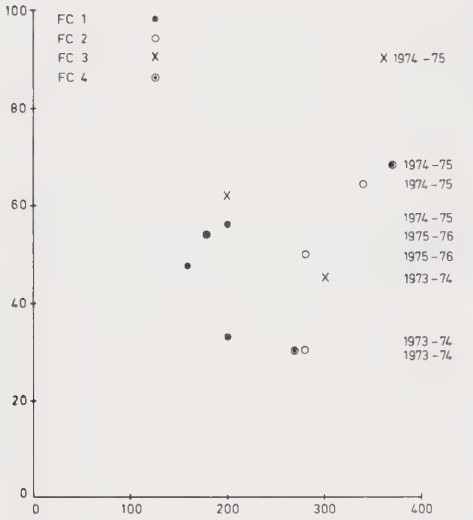


Fig. 9. Calculated gross heave (H) for the upper soil layer (S 1) as a function of frost index (from Stenberg 1977).

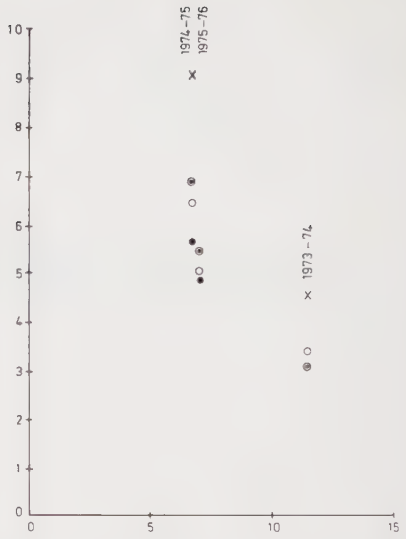


Fig. 10. Calculated gross heave (H) for the upper soil layer (S 1) as a function of frost intensity (From Stenberg 1977).

The causes of the results obtained are hard to define. The frost heaving process can, thermodynamically, be considered as a series of complex states of equilibrium between several parameters and the dependence on the microstructure of the soil is not yet fully explained. Field observations are invariably far more difficult to relate to theory than laboratory tests.

### *Sources of error*

The sources of error relate to the position of the device for determination of vertical movements, the exactitude of the frost index, and the subjective assumption of the level of soil interfaces. The control of the vertical movements had been presumed to be positioned at the interface between two adjoining test soils. Deviations occur, but will be of secondary importance to the main line of reasoning. However, the exact degree of frost heave, penetration and frost index will be affected. The values shown in Tables 1—11, *VTI Meddelande No 41* , will be changed but the main relations would presumably remain constant.

### *Influences of the* in situ *water content on frost heave*

The influence of the *in situ* water must be considered from a thermal point of view. It is obvious that an increasing water content increases the termal conductivity. This ability, however, is hidden

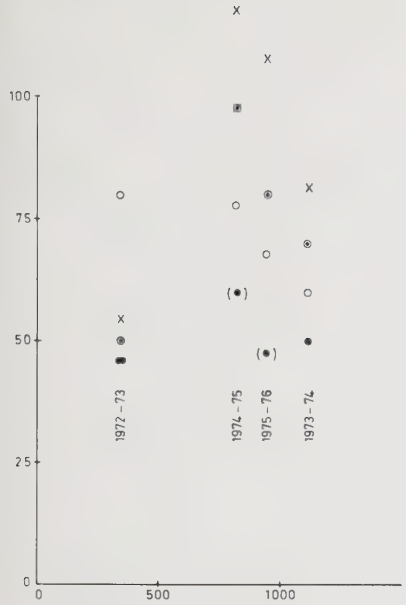


Fig. 11. Net frost heave as a function of recorded frost index during 1973—1976.

by the fact that at increased *in situ* water content the heat extraction, which is necessary to produce the same rate of frost penetration will increase faster. The result will instead be a reduced rate of frost penetration. At the surface this is observed as an increased frost heave. The extracted heat will, therefore, derive primarily from the latent heat of *in situ* water, and secondarily from accumulated water. This is the case with the Sälen-soils.

We can summarize as follows. The increased thermal gradient increases the suction of water to the ice-front. The thermal gradient also increases the heat flow. If the increased flow of water balances the heat flow, then we obtain accumulation of water/ice. If not, we have penetration and a decreasing thermal gradient, which may produce water/ice accumulation. Further discussion of this matter would be unappropriate here. The basic thermal theories are presented in *VTI Meddelande No 106.*

## Hydraulic conductivity

The hydraulic conductivity or permeability is one of the parameters of importance for frost heave. It was not possible to determine the influence of changes in the permeability on the frost heave rate. In theory some differential features of the frost heave process in the separate cylinders can be attributed to the permeability. The calculated differences are, however, so slight that they can be placed within the limits of uncertainty, set by the readings of the gauges. The amount of water transported to the frost front is determined not only by the permeability coefficient but also by the hydraulic gradient which depends *inter alia* on the freezing temperature in the pores as well as the thermal gradient (Loch & Miller 1975, Loch & Kay 1978).

## Load pressure

The reducing influence of load pressure on the frost heave results from the reduced thickness of the adsorption water layers. Each soil particle is surrounded by a polymolecular layer of adsorption At the icefront, regarded as a growing ice-lens, there is an ice/adsorption water interface. The pressure of surcharging soil will be transmitted through the ice-lens, and carried by the adsorption water layer between the particle and ice. The ice-lens growth by adherent water molecules from the adsorption water disturbs the equilibrium, the adsorption water layer com-

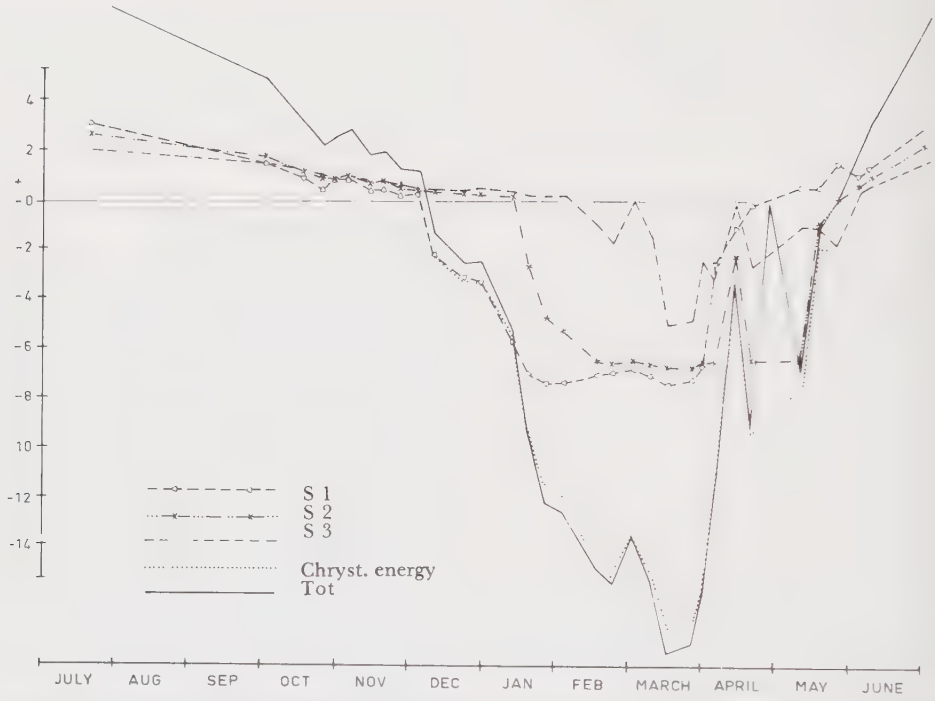


Fig. 12. Thermal energy content of cylinder FC 4 1975 1976. »0» means the level where the average soil temperature is 0° C in frozen state.

pensates this by taking new water molecules from the free »bulk» pore-water. This transport of water will thus depend on *inter alia* the thickness of the adsorption water layers. Generally the water accumulation rate, i.e. the heaving rate, is a hyperbolic function of the load pressure.

Within the intervals of relatively small changes in load pressure the relationships may be considered practically linear. The relationship illustrated in dH/dt=f(P) can be analysed from several angles. For example: Suppose we have a linear relationship within the interval studied and then compare the differences between FC2 and FC3, which have the same soil profile in the frozen zone. From the slope of the lines the following comparisons and conclusions can be made:

a. The same FC during different years – variations in slope depend on the termal conditions.

b. FC2–FC3 during one year – the variations depend on the permeability.

Case a. is affirmative – a high value in 1973–1974, the lowest in 1974–1975.

Case b is affirmative. FC2 has a higher heaving rate than FC3 at the same load pressure. According to diagram 86 (*VTI Meddelande 41*) the permeability is higher too.

Nevertheless we must emphasize that this type of analysis has only theoretical

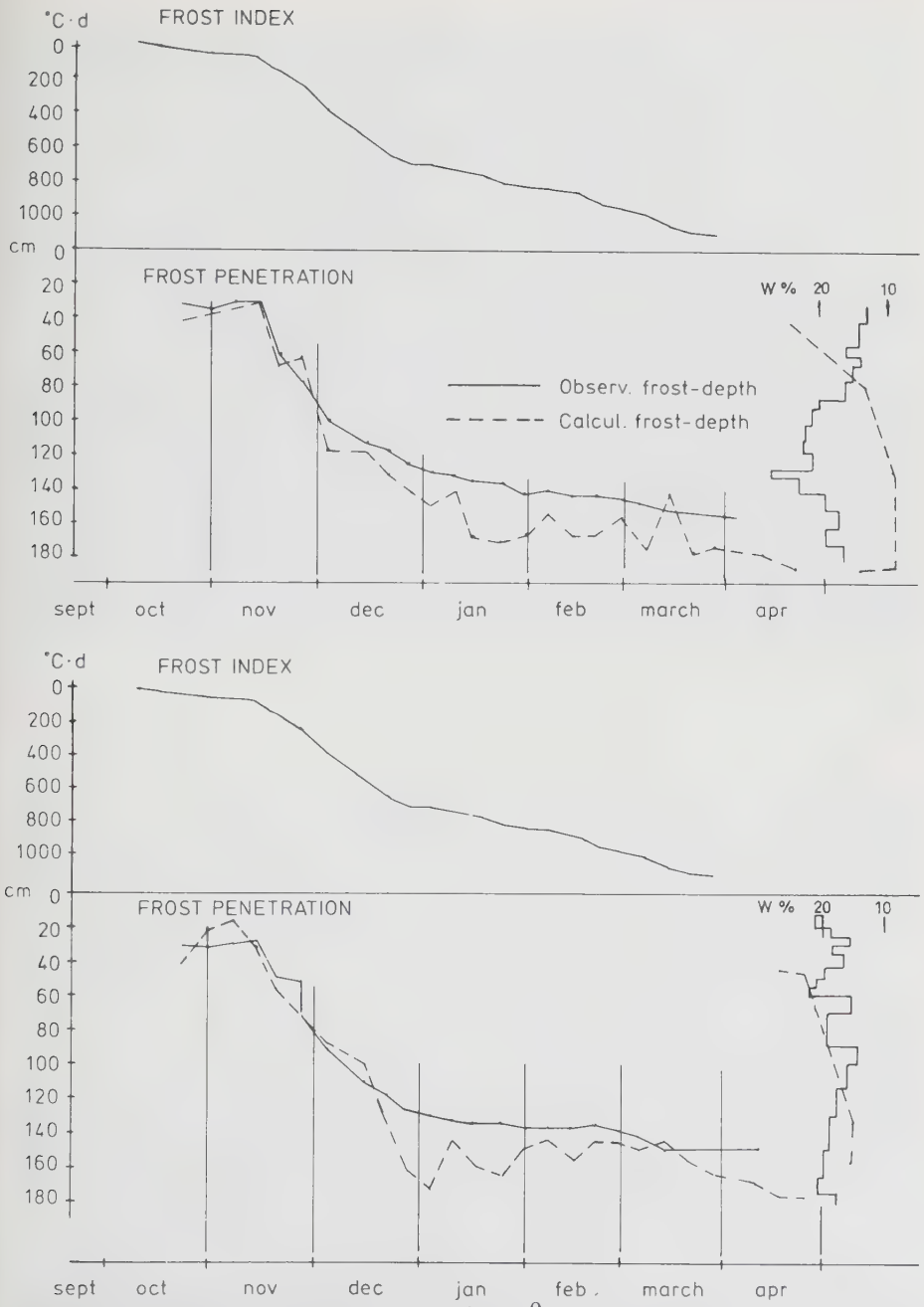


Fig. 13. Observed frost depth and the position of the 0° C-isotherm, calculated from the temperature observations 1973–1974.

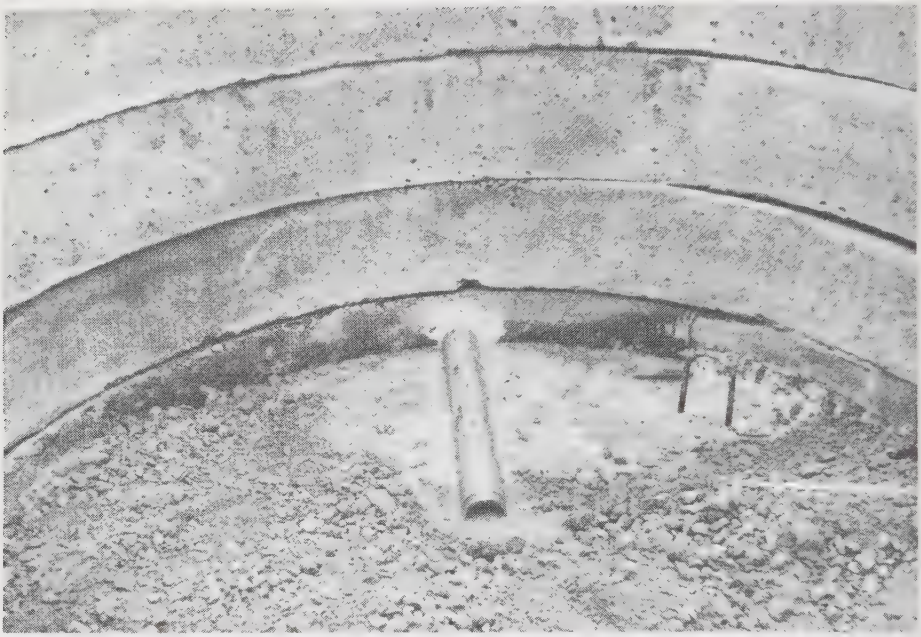

Fig. 14. The water pipe at the bottom is protected from compression by a metal pipe. The bottom layer is of sandy gravel.

significance. The basis is too meagre to allow calculations for the purpose of investigating the influence of different parameters on the frost heaving process, and the results cannot be used in the continued discussions.

The relation between the square root of the inverted heaving rate and the load pressure, found by Beskow (Beskow 1935), was tried, but it was still not possible to solve and quantify the influence of the load pressure. The difficulties are mainly caused by the simultaneously decreasing thermal gradient with increasing frost depth by the need for complicated calculations. As was mentioned earlier, the frost heave is, *inter alia*, a function of the course of frost penetration and the flux of water to the ice-front. There are no indications that the water content *in situ* would be comparable in FC2 and FC3.

The load pressure $P_1$ was calculated as the sum of surcharging soil and the capillary water height, which is equal to the distance to ground water level. The calculations were performed on the assumption that there is no air in the frozen soil.

### *Flux of water*

The water intake by the cylinders FC1—FC4 was measured during the frost heaving period. Laboratory experiments have established the fact that accumulated volume of water is directly proportional to frost heave. Therefore it was puzzling to find this not the case in the Sälen freezing tests. Accumulated volume of water could only explain half of the

Fig. 15. Compaction of soil. The frost heave indicator can be seen in the middle part. The space between the outer and the inner cylinders is filled with mineral wool.

observed heave. This deviation was to a great extent reduced by the reduction of the *in situ*-heave (See also Appendix 23, *VTI Meddelande No 101*). In the preliminary report (*VTI Meddelande No 41*) the cause was assumed to be a porous structure in the frozen soil.

Laboratory tests are carried out under nearly optimal frost heaving conditions. In these cases the error introduced by neglect of the *in situ*-heave will be of secondary importance. The same simplification cannot be made when dealing with field frost heave. As shown in the Appendix, *VTI Meddelande No 101*, the *in situ*-heave will be around 4 cm.

The calculated values of the dry densities will not be changed, as the *in situ*-water was then taken into account (Appendix I, *VTI Meddelande 41*).

*Water content in relation to observed frost heave*

In theory, the amount of crystallized water per unit of time can be approximated to heat flow, as when samples are studied in a laboratory freezing test. With large samples this same approximation can be made only for frost susceptible soils.

When studying diagrams 5—16 (*VTI Meddelande 41*), frost heave should be related to the water content in teh frost penetrated soil. However, there is e.g. no evidence of increased water content at reduced frost penetration or vice versa, to relate to observed frost heave rate.

Such a reasoning presumes a constant water content in the unfrozen soil. According to redistribution of the *in situ*-water during freezing, it is not possible

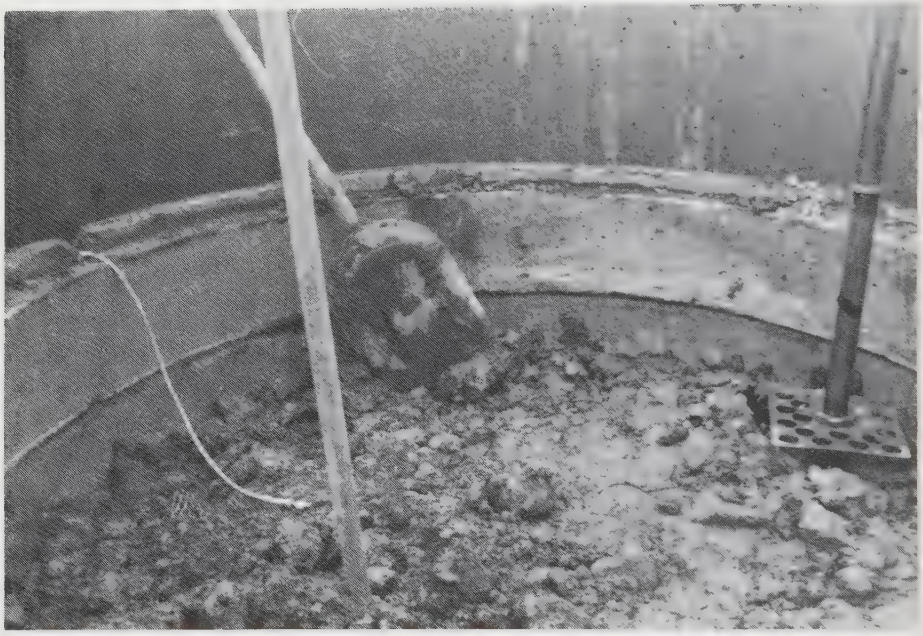

Fig. 16. The resistance thermometer and the frost heave indicator at the interface between two soil layers. The position of the frost depth indicator is marked by the wooden peg.

to draw any conclusions of the ice-content distribution in a frozen soil from observed frost heave.

### *Determination of water content and dry densities*

The water content of the frozen soil was determined from samples obtained by drilling at optimum frost heave. Knowing the degree of heave in each soil layer and assuming the heave to result from accumulation of water and volume change at the transition water to ice, the *in situ*--water content and dry densities of the soil layer can be calculated. This is shown in Appendix to *VTI Meddelande No 41.*

### *Flow of water to the ice front*

Darcy's law was unvoked in order to envisage the apparent flow of water to the ice-front.

The permeability of the soil pile was calculated with regard to the change in porosity of the layers as compared with the laboratory determinations.

Thus the developed suction or pressure difference was calculated from the heaving rate and the frost depth and the results are presented in tables both with and without regard to the *in situ* frost heave rate. The magnitude of the developed pressure difference is heavily dependent on the permeability coefficient.

Fig. 17. Rockwool insulation of water pipe. To the right is the instrument and water containing shed under construction.

## Methods for calculation of pore pore radius, $r_v$

*VTI Meddelande No 101* discusses the water transport, according to present theories. The transport mechanism in the adsorption layer is not fully understood which governs the calculation method used. However, the calculations must be questioned as to the execution presented in Table 46 (*VTI Meddelande No 101*).

The suction $P_d$ which gives rise to the hydraulic gradient determining the water transport to the freezing front, has been calculated from Darcy's law (Appendix 23, *VTI Meddelande No 101*). When the pores are partly frozen, the water flows through the unfrozen film of adsorption water. These »capillaries» are much smaller, and thus the potential difference, expressed as suction, must be much higher than calculated. The calculations can be performed from

a. Darcy's law, in which case the permeabilitycoefficient $k_p$ must be considered to express a resistance to flow of a more general character.

b. Poiseuilles' equation, where $P_d$ is inversely proportional to the capillary radius $r^4$ The result also depends on the number of »capillaries» per unit area perpendicular to flow.

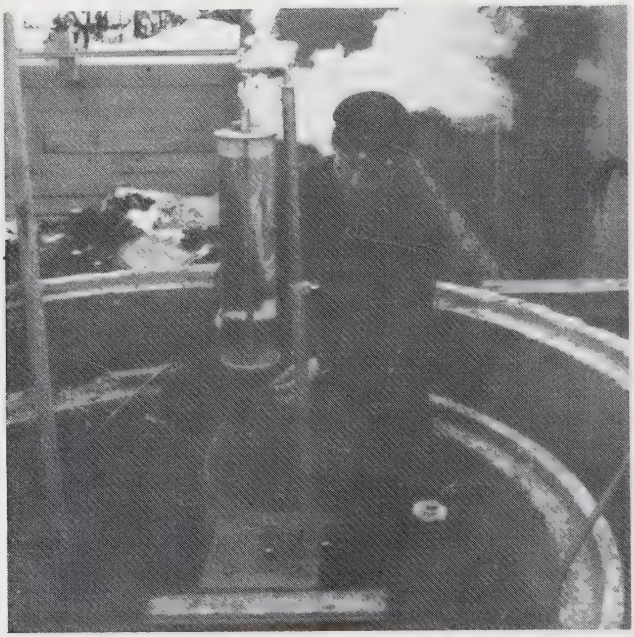

Fig. 18. Dry densities of the soil were determined by a water volumemeter.

It is also possible to use

c. the Hele-Shaw equation

$$dV/dt = (D^3/12\,\eta)\, dP/dl$$

for laminar flow in a thin plane crack. It is analogous to Poiseuilles' equation. D is the width of the crack.

These arguments are based on the fact that the energies governing the frost-heaving process are developed in the adsorption-water layers in contact with growing ice-lenses.

Different methods were applied in the calculations in order to envisage the effective particle and pore sizes.

1. Use of d10 as an average effective particle size.

2. Capillarity testing.

3. Determination of permeability. This was treansferred to an equivalent pore radius giving the same flow of water per square unit as was measured by the laboratory determinations.

1. Use of d10 as an avergage effective particle size gives:

| | Particle size | Pore radius |
|---|---|---|
| Fine silt | $d_{10}=3\times10^{-4}$ | $r_v\simeq3\times10^{-5}$ cm |
| Coarse silt | $d_{10}=15\times10^{-4}$ | $r_v\simeq15\times10^{-5}$ cm |
| Till | $d_{10}=4{,}5\times10^{-4}$ | $r_v\simeq4{,}5\times10^{-5}$ |

Estimating the approximate capillary

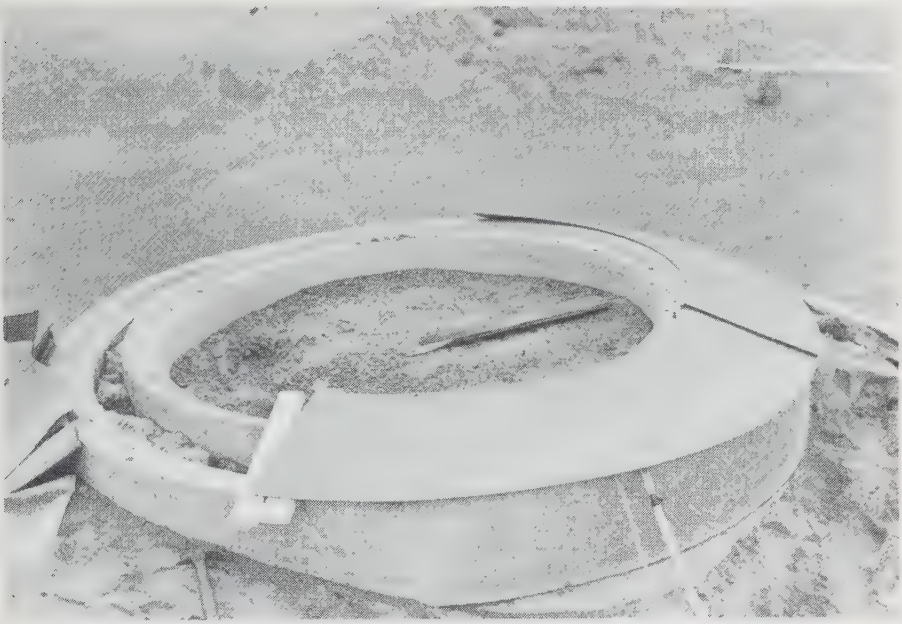

Fig. 19. The insulation was protected against precipitation.

height of water

a. from Beskow (the expression is derived for uniform soils)

$$H_k = \frac{0{,}06}{d_{10}} \text{ (m)}, \; d_{10} \text{ in mm}$$

b. and Terzagi

$$H_{k,T} = \frac{(1 \sim 5) \times 0{,}1}{0{,}64 \times d_{10}}$$

2. Capillarity determinations in the laboratory (*VTI Meddelande No 41).*

The pore sizes were calculated from the calculated subpressures according to (a), (b), and (2) from the Laplace equation

$$\Delta P_w = 2\sigma_{aw}/r_v$$

The reaults are shown in Table 2

According to Loch & Miller (Loch & Miller 1975) the capillarity is a reliable

*Table 2.*

| *Soil* | *Beskow* (kPa) r cm | *Terzagi* (kPa) r cm | *Capillarity* (kPa) r cm |
|---|---|---|---|
| Fine silt | 200 $7{,}5 \times 10^{-5}$ | 50–250 $6–30 \times 10^{-5}$ | 72 $21 \times 10^{-5}$ |
| Coarse silt | 40 37,5 | 10–50 30–150 | 60 25 |
| Till | 125 12,0 | 35–175 8,6–43 | 53 28 |

Fig. 20. The four freezing cylinders. Behind them the tempered instrumental shed is seen.

method for the estimation of pore radius. However, they found a value between 4—4,8 of the ratio $r_p/r_v$ instead of 5, which has been used in the calculations presented above.

Relying on the results from the capillarity determinations the pressure difference $P_{iw}$ was calculated.

| | | |
|---|---|---|
| Fine silt | $\Delta P_{iw}$=28,6 kPa | 1 Pa=10 dyn/cm$^2$ |
| Coarse silt | $\Delta P_{iw}$=24,0 | |
| Till | $\Delta P_{iw}$=21,0 | |

3. Permeability measurements give the flow according to Darcy's law. This flow was transformed into a comparable flow through an equivalent capillary, by use of Poiseuilles' equation. The radius was calculatedfrom the equation derived in *VTI Meddelande No 101.*

$$r^2_{equ} = \frac{8 \times \eta}{n \times} \frac{\times k_p}{\rho_w \times g}$$

The results obtained by the laboratory tests were used to calculate the equivalent radius $r_{equ}$:

| | | |
|---|---|---|
| Fine silt | n=24,6% | $k_p=2\times10^{-6}$ (cm/s) |
| | $r_{equ}=3{,}4\times10^{-5}$(cm) | |
| Coarse silt | n=25,6% | $k_p=1\times10^{-5}$ |
| | $r_{equ}=7{,}5\times10^{-5}$ | |
| Till | n=21,5% | $k_p=8\times10^{-7}$ |
| | $r_{equ}=2{,}3\times10^{-5}$ | |

Fig. 21. A typical view when starting the registration.

The adsorption forces, must counteract the suction $p_d$ but also the load pressure $p_1$. As $P_d$ and $P_1$ are considered to be additives the effect exerted, $E_a$, per unit area can be calculated (*VTI Meddelande No 41, p. 24*). If $P_1$ and $P_d$ are expressed in dyn/cm$^2$ and $\Delta H$ in m, we get

$$E_a=(P_1+P_d)x\Delta Hx10^{-7} \quad J/cm$$

where $\Delta H$ is the degree of heave. The amount of water transported in the adsorption film water at constant $P_d$ is dependent upon the film thickness. The thermodynamic condition of equilibrium film thickness is also a function of load pressure and freezing-point temperature, where the latter also depends on the ion concentrations. These complicating factors are mentioned for the sake of information and will not be considered later in this work.

The Sälen test results cannot be used in such a calculation, being outside the scope of this study. Nor do the test resuls scope of this study. Nor do the test results allow precise calculations. Concerning laboratory tests, the use of Laplace' s equation

$$\Delta P_{aw}=2\sigma_{aw}/r$$

$\Delta P_{aw}$=capillary suction (dyn/cm$^2$)

$\sigma_{aw}$=surface tension (dyn/cm)

r=capillary radius (cm)

on capillary determinations is recommended. Once the radius and $\sigma_{iw}$, are known $\Delta P_{iw}$ can be calculated and compared with the test results. Provided that freez-

ing takes place under comparable conditions, e.g. with the same overburden and thermal gradient. It has not yet been possible to perform such comparative freezing tests on the Sälen soils.

## Water transport in frozen soils

It is extremely hazardous to estimate the permeability coefficients and the driving potentials in freezing soils.

It has been shown that frozen soils are permeable. Williams (Williams 1977) measured permeability coefficients of $10^{-11}$ m/s. In frozen soils we can ascribe the water movements to flow in the unfrozen adsorption layers. This reveals the temperature dependence since the temperature affects the thickness of the adsorption layer. The use of Poiseulles' equation or Darcy' s law is inappropriate in this context.

The concept of secondary frost heaving and the mobility of the pore ice proposed by Miller is worthy of mention. His theoretical discussion of the secondary frost heaving mechanism is, to a great extent, supported by laboratory experiments. According to him, the flow of water in a partially frozen soil, i.e. in the frozen fringe, is bound not only to the unfrozen adsorption film water layers, but also to a mechanism of freezing and thawing of a pore ice body surronded by film water. The transport is a seriesparallel transport of mass and heat in which ice is transformed to adsorption film water on the »windward» side (ice/water interface), while water continuously becomes ice on the »leeward» side. This involves movement of water and internal exchanges of latent heat (Miller *et al* 1975). An important fact is that this theory, although not yet fully accepted, allows for higher heaving pressures than the capillary model. Heaving pressures higher than expected have been recorded by several scientists.

It has been shown that both the heaving rate and the heaving pressure increase with the increasing thermal gradient. This supports the belief that the net heat flow determines the optimum heaving rate at constant pressure with no penetration of the 0° C isotherm, and that the thermal gradient at the ice front affects the potentials needed to cause the hydraulic flow, which equilibrates to heat flow (latent heat when ice-lensing occurs). Frost penetration will result when this primary condition is not fullfilled. This does not contradict the existance of a »shut off» pressure, which is the hypothetical pressure at which the water flow to the ice-front ceases under prevailing thermal conditions.

Apart from the driving potentials of hydraulic flow, the properties of the film water are of importance. In brief, film water is known to exist down to -30° C. The thickness also depends on the surface energi of the mineral particla, and on the ion concentration in the film. The magnitude of an »effective» viscosity of film water in contact with ice is considered to vary between those of bulk water and ice, depending on the number of molecular water layers. The viscosity increases with a decreasing number of water layers.

## Dismantling of test cylinders

At the end of August, 1977, the dismantling of the freezing cylinders and the accompanying test samples for determinations of dry density and water content showed a higher water content in the silty

soils. This fact supports the assumption of complete saturation in the unfrozen state. However, the calculated values of the dry densities presented (Tables 44–45, *VTI Meddelande No 101*) are too high in relation to the »densities of August», but they are in agreement with observations within the margin of error. The differences are supposedly due to an under–estimation of the draining capacity of the soils. Drainage proceeds until late autumn. It was also noticed, from the soil found in between, that the rings were lifted during frost-heaving. The extent to which this was caused by the adfreezing and/or heaving by intercalated soil material is unknown.

## Freezing cylinder No 5 (FC 5)

Early in the winter of 1974 a fifth cylinder, FC 5, was constructed. Thu purpose was to test new methods of measurement. The indicator of vertical soil movements was changed from manual to automatic readings. This was effected by resistance measurements. The other metod was intended for water content determinations. Stationary soil resistivity transducers were applied at helical intervals of 100 mm. To avoid precipitated water FC 5 was fitted with a perforated hood allowing for air circulation.

The influence of the hood was observed through delayed freezing and thawing in comparison with the open cylinders, FC 1–FC 4. The cause is preumably the difference in radiation energy exchange.

The resistance measurements indicate a continuous decrease in water content which begins in autumn, endures throughout the period of freezing and is reversed during the thaw period. This indicates a continuous increase in desaturation of the soil. The degree of this desaturation will affect the flux of water to the ice front. The result implies a suction developed at the ice-front and active, through decreasingly, down to the ground water. If the interpretation is correct, which will be shown by future experiments, this theory may be helpful in estimating sub-pressures in soils. As it is impossible to use tensiometers in freezing soils, resistivity measurements might be a means to circumvent this problem. This is important for the frost heave mechanism.

*Resistivity measurements in FC 5*

As described above, and reported in *VTI Meddelande No 10* , a fifth cylinder was constructed in 1974. In order to record the changes in water content at different levels during frost heave, a number of soil resistivity indicators constructed at *VTI* were installed. Initial laboratory tests had shown that the dry densities did not affect the resistivity but that the water content of the soil did, i.e. the degree of water saturation. Continued tests showed a logarithmic relationship between water content and the measured resistance of the soil,

$$\log R \approx f(\frac{1}{w}) \times j$$

where j is a soil constant. Although difficulties ensued in the translation of the test results into determinations of water content, these showed a continuously increasing degree of desaturation from the ground water level. As the desaturation increases with time, during freezing, it cannot be ascribed only to hydrostatic conditions. The statement may seem puzzling on study of Table 9 (*VTI Meddelande 101*). The reason is

that, in the early winter, the soil was packed while only slightly moist. The water was added by capillary suction. The winter of 1974–1975 cannot therefore be used in the discussion. The next winter showed results difficult to interpret. This presumed to be due to the equipment and the time needed for the readings. After the development of a faster and semi-automatic device, the sources of error were to a great extent eliminated. Accordingly we shall only consider the readings from 1976–1977.

The interpretation of the results is not unequivocal but may offer some indications. However, I find it worth mentioning.

## Soil temperature

Soil temperature readings were made on resistive thermometers (Pt 100). The resistance was read by a Wheatstone bridge, but from the autumn 1974 onwards a multimeter was used. The accuracy was within 0,3 °C. The temperatures at each soil interface were read weekly. Teh results are presented in diagrams illustrated in Fig. 7.

The soil temperatures were primarily used to calculate the change in the energy content of the soils. The results are presented in diagrams for each freezing cylinder during the period 1973–1977. An example is given in Fig. 12 (Diagram 38, *VTI Meddelande No 101*). When calculating the frost depth, the uncertainty in the temperature readings can give great differences from the depth given by the frost depth indicator at small thermal gradients.

This will be evident when comparing the curve of total energy content with the frost penetration curves. The latter are based on the frost depth indicator.

A comparison between calculated frost depth and frost depth read from the indicator is shown in Appendix 20, *VTI Meddelande No 101*, Fig. 13. The two curves can be said to agree fairly well, taking only the frost depth into account. But for a mathematical treatment, such as thermal calculations, a decision must be made concerning the method of preference. In this presentation I only want to point out these differences. Sources of errors can be found in both methods on critical scrutiny.

The heat is easily calculated from the change in energy content per interval between two temperature readings. This is expressed by the inclination of the energy content curves.

The heat flow was also plotted against the thermal gradients. According to Fourrier's equation, the ratio between heat flow and the thermal gradient is proportional to the thermal conductivity. However, this relationship was not established. The deviation in the calculations from values reached in laboratory experiments (Skaven-Haug 1971), thermal conductivity being too large.. This deviation is probably due to the temperature variations between the readings. The conclusion will therefore be that weekly readings are not sufficient, providing only for rough calculations and approximate data.

## Conclusions

The primary being to study the field testing method as a tool for classifying the frost susceptibility of soils, the following conclusions can be reached.

1. The frost heaving capacity of soils can be mutually evaluated.

2. Layering in a soil profile affects the frost heaving. The extent of the influence from sublayers of different soil materials depends on the mode of freezing, i.e. on frost intensity.

3. The influence of permeability could not be determined although it must still be considered.

4. The influence of overburden cannot be evaluated. The effect is masked by the simultaneously lowered thermal gradient.

5. The thermal gradients developed in the freezing soil seem to be the domination frost heaving parameter, apart from the physical properties of the soils.

Full scale experiments should be carried out in similar types of freezing cylinder. To exclude the difficulties which arrise in the interpretation and evaluation of the frost heaving parameters, the layering of different soils should be avoided. Layering, of only two soils, would then be tried as a second step. As a last and final step towards a full understanding of soil frost heaving, lenses or layers of different soils may come under consideration.

The important question of how, and to what extent, the ground water level and overburden pressure affect the frost heave, might also be answered through the use of such techniques.

Other questions arising during the experimental period, are concerned with empirical physics. The answers to those posed will be briefly summarized.

1a. There is some connections between observed frost heave and frost index as studied over one winter season.

1b. There is no evidence of a direct relationship between observed frost heave and frost index when studied over a period of years.

The frost index cannot be used in predictions of degree of frost heave unless, for instance, at least 50% deviation is allowed.

2a. There are indications of a relationship between the course of frost penetration and frost heave. However, the relationship is partly masked by the overburden pressure and especially by the thermal conditions.

2b. Frost penetration can be predicted with the help of the frost index. But the precision will be reduced with increasing frost depth.

3a. Frost index is not the only parameter determining the heat exchange from a soil surface. Radiation and wind conditions must be considered in calculations of heat exchange.

3b. At present frost index cannot be used in calculations for prediction of the degree of frost heave. It may still be a useful parameter if the influence of heat can be established.

4. The experioments made by the Sälen-project cannot answer the question of heat exchange.

According to these answers further experiments should include instrumentation for evaluation of the exchange of radiation energy and the influence of wind speed. This could be done by temperature measurements on a reference surface, over a soil pile designed and properly

equipped to give reliable results.

It is generally accepted that the thermal conditions are of utmost importance for the measures taken to protect soils from frost.

Different insulation materials are widely used to protect soil from frost. A knowledge of the behaviour of different soils during freezing and especially at varying thermal gradients at the freezing front is essential for economic assessment of the need for insulation.

The design of full scale freezing tests according to the one presented, incorporating the improvements suggested, would offer results meeting present needs, as well as provide a basis for solution of future problems, and for further experiences in field research.

Although this type of experiment is expensive in the beginning, the future costs would be reduced as the initial material and developed equipment would still be available.

The frequently performed tests of the frost susceptibility of soils by laboratory freezing methods still give only relative results. Simple field tests of suggested design which reduce the number of will provide an exellent basis for determination of the exact behaviour of soils under given freezing conditions, supplementing the laboratory freezing tests, and making them more reliable for predicting field frost behaviour.

## Summary

The »Sälen-project» was commissioned by the National Swedish Road Administration for the purpose of obtaining a better understanding of the behaviour of some frost heaving soils during freezing in the field.

The experiment was carried out as a full-scale laboratory freezing test. The four freezing cylinders, consisting of loose concrete rings, were filled with three different soils. An outer cylinder carried the surrounding soil pressure, an inner cylinder being filled with the test soils. The space in between was packed with insulating material (Rockwool). The three test soils, coarse silt, silt and sandy silty till, were arranged in layers of 4 different combinations. A ground water level was simulated by piped water containers, one for each freezing cylinder. Thus the water intake to the different cylinders could be measured. Each freezing cylinder was instrumented in such a way that the frost heaving of each single soil in its particular position could be measured, as well as the frost penetration. A resistant thermometer was also placed at each spoil boundary.

The results show uncertainty in the correlation of frost heaving to the frost index. The variation in frost depth with frost index, hawever, is far less. The occurrence of frost heaving depends to a great extent on the frost intensity during the initial stage of the cold period. One, at the beginning, fairly mild winter (1974–1975) with a frost indes of 850° Cxd could in the case of coarse silt and silt cause a frost heave 80% higher than an, at the start, cold winter with a frost index of 1150° Cxd. This effect is mainly located to the upper layer, and does not necessarily contradict the empirical relationship found by Gandahl. Nevertheless there seems to be some connection between the degree of frost heave and the frost index. But at the same time this relationship seems to depend on load pressure. The increase in the rate of frost heave with the frost intensity was most obvious in the upper soil layer, and decreased with continued frost penetration.

To establish the impact of load pressure the rate of frost heave this relation was examined. There was, however, no simple connection and the thermal conditions, chiefly the thermal gradient, are presumed to be the important factor.

Assuming that the registered frost heaving is caused by water accumulation, the dry densities of the soils were calculated before freezing, at maximum frost heave and in an unfrozen, undrained state, corresponding to the beginning of thaw with its consequences in lowered bearing capacity.

To obtain an understanding of the energy conditions at the frost front, the dynamic subpressure was calculated from registered frost heave rate. These calculations were carried out under very simple conditions. The results showed a magnitude of $\sim$300 Pa (3 g/cm2) in the initial stage which later decreased towards Pa -2 with increasing frost depth. These figures are heavily dependent on the permeability of the soil and its frost susceptibility.

Part II of the Sälen report deals with the thermal measurements. This section is introduced by a basic description of the transportation of water to the ice front. Standard methods such as $d_{10}$ as an effective particle size, capillarity and permeability determinations were used in calculations of the pore radius, equivalent to observed flow of water. The differences between the obtained radies showed a magnitude of 10 according to the method used. A further discussion of the flow mechanism of water, and the influence of load pressure and thermal gradient is presented, and the concept of secondary frost heave briefly defined. Recent laboratory experiments performed by Loch and Kay demonstrated how variations in the thermal gradient and overload affects the frost heaving rate.

Dismantling of the freezing cylinders showed that the rings had welded together and lifted apart by the frost heaving forces. This was especially obulous in the silt of FC 3.

In FC 5, which was fitted with a hood, the frost penetration started later and lasted longer than in the open cylinders. This effect was assumed to depend on the reduction or absence of climatological factors such as radiation energy and wind speed.

The changes in resistance recorded by the resistivity meters could not be transferred into water content.

The measured soil temperatures were used in calculating the thermal gradients and total change of heat energy content in the freezing cylinders. In this context the correspondence between the frost depth observed by the indicator and the calculated $0^{o}$ C-isotherm was examined. The differences are mainly due to the precision of the position of thermometer. The lack of correspondence between the thermal gradient and calculated heat flow is mainly due to the low frequency of the readings (one per week).

In Part III the thermal conditions of water accumulation as ice at the frost line are discussed. The discussion is greatly simplified and restricted to the thermal conditions of ice-lens formation and frost penetration.

The equations deduced are introduced to provide a basis for the evaluation of the frost susceptibility testing of soils with regard to the heat flow parameter. In the fundamental form the equations are given, they can also serve as a basis for the thermal part of a mathematical treatment of the frost heaving process.

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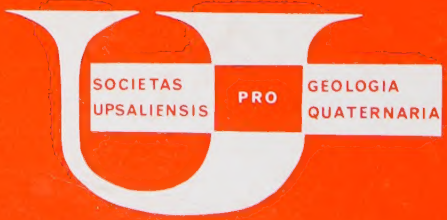
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